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This research showed the bow shock formation in a complex plasma, where plasma particles and charged dust particles form a complex entity. The formation was visible by naked eyes through the illumination of laser light on dust particles. The supersonic flow was possible to make in a complex plasma since dust acoustic wave is characterized by a sound speed of a few cm per second. This observation is important as it is a good representation of bow shocks commonly observed in planetary magnetospheres.
This experiment showed the vortex formation and mass ejection in a complex plasma. Movement of dust particles is visible through the illumination of dust particles by laser light. The observation clarified the vortex physics commonly observed in nature such as tornados and typhoons, and even in the universe such as solar mass ejection.
Molecular dynamic simulation of a complex plasma showed the formation of double helical structures of dust particles. The simulation and theory showed that a complex plasma characterized by its strongly coupled state could play a role in the understanding of structural formation of matters in general.
Experiments, computer simulations and theoretical studies have shown that a complex plasma is rich research field to understand basic physics of various phenomena through the observation of dust particles by naked eyes with the help of laser irradiation. This research team has shown that a complex plasma is opening a new field in the well-established plasma physics.

15. SUBJECT TERMS
Plasma Physics, Magneto-optical imaging , Space Plasma Physics , Multiscale Phenomena

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Final Report

on

Structure Formation in Complex Plasma

-Quantum effects in cryogenic complex plasmas.

AOARD-124077

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to
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Abstract:

Research project AOARD-124077 (FA2386-12-14077) with a title "Structure Formation in Complex Plasma - quantum effects in cryogenic complex plasmas," was carried out at the Complex Plasma Laboratory of Yokohama National University from the period June 28, 2012 to June 27, 2014. The project was carried out by a principal investigator, Professor Osamu Ishihara, in collaboration with research associate Dr. Yoshiharu Nakamura, a senior technical advisor retired from Institute of Space and Astronautical Science of JAXA, Dr. Masako Shindo, a research associate, Dr. Yoshifumi Saitou, a research associate, Dr. Arup Choudhury, a postdoctoral fellow, and visiting scholars Dr. Alex Samarian, Research Scientist of University of Sydney, and Prof. Sergey Vladimirov, Professor of University of Sydney. Dr. Alex Samarian stayed in Yokohama from 2012.9.26 to 2012.12.20 and 2013.2.1 to 3.15 and Professor Sergey Vladimirov stayed in Yokohama from 2012.11.05 to 2013.4.30 and 2013.7.01to 2014.1.31.

During the period, we have published 9 papers in professional journals and presented our results in domestic as well as international conferences. Professor Ishihara gave an invited talk at the Joint EPS/ICPP (the 39th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics) in Stockholm. Also Osamu Ishihara gave an invited talk at the 2012 Fall Meeting of Japanese Physical Society Conference.

Personnel

(1) Osamu Ishihara, a principal investigator and a director of the Complex Plasma Lab at Yokohama National University
(2) Dr. Yoshiharu Nakamura, a senior technical advisor, retired from ISAS (Institute of Space and Astronautical Science), JAXA (Japan Space Exploration Agency)
(3) Dr. Masako Shindo, a research associate
(4) Dr. Yoshifumi Saitou, a research associate
(5) Dr. Alex Samarian, Research Associate
(6) Prof. Sergey Vladimirov, visiting professor (Professor, university of Sydney)
(7) Dr. Arup Choudhury, a postdoctoral fellow （2011.9～2012.8）
(8) Ms. Naomi Shibuya, secretary

Introduction:

Complex plasma is a plasma in which electrons, ions, neutrals and dust particles of mic ron size are present. Dust particles are negatively charged in a plasma and characterized by th e heavy masses. Conventional plasmas are characterized by the kinetic energy of plasma partic les much larger than the electrostatic interaction energies. Such a nature is known as a weakl y coupled state, while the dust particles, with huge charges are characterized by the larger ele ctrostatic interaction energies compared with the kinetic energies of dust particles. Such a natu re is known as a strongly coupled state.

Weakly Coupled: plasma kinetic energy >> electrostatic interaction energy

Strongly Coupled: dust kinetic energy << electrostatic interaction energy

Strongly coupled charged dust kinds of particles are necessarily connected together and form various structures in a plasma. The kinetic energy of dust particles are reduced when the complex plasma is in

a cryogenic temperature. Our project is focused on a complex plasma to study structure formation of dust particles in complex plasma in low temperature.

Experiments

(1) The YCOPEX (Yokohama Complex Plasma Experiment) is the Pyrex glass tube of 100cm in length and 15cm in inner diameter. The tube is connected to the bellows at the left end. A stainless steel plate of 2mm in thickness of 14.8cm in width and 90cm in length is placed in the middle of the tube along the axis. Two piezo-electric buzzers are set under the plate at 5cm from the edge of the plate. Silica micro-particles of 5 μm in diameter and the density of 1.6g/cm^3 are contained in the buzzers. The hole of 1mm in diameter is made over each buzzer. Several spherical plastic beads of 1.5mm in diameter are also contained in the buzzers to shatter the powders to pieces if they are coagulated together. When the dc voltage of 0-10V is applied to the buzzers, they oscillate with a frequency of 2 kHz so that micro-particles jump up from the holes. At both edges of the plate, two stainless steel foils of 0.1mm in thickness and 2cm in height are placed as fences to confine particles longitudinally. Particles are radially confined by the ion-sheath formed in front of the surface of the glass tube.

Bow shock formation:

A bow shock is observed in a two-dimensional supersonic flow of charged micro-particles in a complex plasma device YCOPEX. A thin conducting needle is used to make a potential barrier as an obstacle for the particle flow in the complex plasma. The flow is generated and the flow velocity is controlled by changing a tilt angle of the device under the gravitational force. A void, microparticle-free region, is formed around the potential barrier surrounding the obstacle. The flow is bent around the leading edge of the void and forms an arcuate structure when the flow is supersonic. The structure is characterized by the bow shock as confirmed by a polytropic hydrodynamic theory as well as numerical simulation. (Paper #1)

(2) YD Experiment (Yokohama Dewar)

Experimental setup YD is a glass tube contained in a silver-coated glass Dewar bottle (glass cryostat) with the inner diameter of 9.6 cm and the height of 80 cm. The Dewar bottle is filled with liquid helium or liquid nitrogen and is inserted in a liquid nitrogen stored in an outer Dewar bottle with the outer diameter of 20 cm. The silver coated Dewar bottles have 1 cm wide vertical uncoated slit for observational purpose. YD can be operated either with a glass tube installed inside or without glass tube. The glass tube is inserted in the inner Dewar bottle. The typical glass tube is 70 cm in length consisting of a thin upper part of 60 cm in length with 1.6 cm in diameter and a thick lower part of 10 cm in length with 4.8 cm in diameter. Various sizes of galas tubes were used. The glass tube is connected to an external stainless steel pipe at the flange attached to the inner Dewar bottle. The temperature of the gas in the glass tube is controlled by the cryogenic liquid, liquid helium (<4K) or liquid nitrogen (77K), contained in the inner Dewar bottle. The outer Dewar bottle contains liquid

nitrogen (77K) to maintain the inner cryogenic temperature. An rf helium plasma with a neutral gas pressure $P = 0.1 \sim 100$ Pa is produced by applying the rf (13.56 MHz) power of 1 ~ 7 W between the electrodes mounted in the lower part of the glass tube. The plasma is characterized by the electron density of $n_e \sim 10^{15}$ m^{-3} and electron temperature of a few eV, while ions lose their kinetic energy through collisions with cooled neutrals. Acrylic particles (dust particles) of $a = 0.4 \sim 10$ μm in radius with a mass density of $\rho_d = 1.2$ g/cm^3 are dropped from the dust dropper situated about 80 cm high from the bottom of the glass tube. The dust particles charged in the plasma are suspended around an equilibrium position, about a few centimeters from the bottom of the tube, where the upward sheath electric force balances with the downward gravitational force. The particles illuminated by red (λ = 671 nm) or green (λ = 532 nm) laser are visible by naked eyes, while the motion of dust particles are recorded through the slit by a high-speed CCD camera at a frame rate of 200 ~ 400 fps and analyzed by PTV (Particle Tracking Velocimetry) method. To observe vertical motion of dust particles in the plasma, a few particles are dropped from the dust dropper. The dust particles are accelerated in the long glass tube under the gravity. The dust particles are immediately charged after entering the plasma, go further below the equilibrium position and go deeper in the sheath. Electric force acting upward on the charged dust particle in the sheath suspends the dust particle and the dust particle moves upward against gravity.

Dust particles form a fat torus structure in a complex plasma with a magnetic field. The toroidal axis is perpendicular to the magnetic field. The dust particles rotate both in the toroidal and the poloidal directions. Under a certain value of the magnetic field and a certain value of the neutral pressure higher than certain values, the dust particle ejected upward from the disk surface. This phenomenon is based on the dust particle motion but it is explained in a context of the vortex ring of the fluid dynamics. (Paper #5)

Collective motion of charged dust particles, levitated in a disk and a ring that forms in cylindrical electrodeless RF plasma with an axial magnetic field, was investigated experimentaly. The measured angular velocities of the disk and the ring are less than 10rad/sand less than 8rad/s, respectively. We found that the angular velocity strongly depends on the gas pressure and the strength of the magnetic field while the RF power does not significantly influence the rotation of the dust structure. (Paper #7, #9)

Dynamics of microscopic charged dust particles in cryogenic condition is studied experimentally. Dust particles were free falling through the liquid helium (LHe) vapor as well as through LHe. In the liquid, particles start to go up toward the surface. It was found that dust particles are charged negatively in vapor plasma, but lose the negative charge and became charged positively in the liquid, which is confirmed by the examination of the particle dynamics. Based on dust trajectories observed, the charge values for the dust particles were calculated. (Paper #8)

Simulation

Structures of Coulomb clusters formed by dust particles in a plasma are studied by numerical simulation. Our study reveals the presence of various types of self-organized structures of a cluster confined in a prolate spheroidal electrostatic potential. The stable configurations depend on a prolateness parameter for the confining potential as well as on the number of dust particles in a cluster. One-dimensional string, two-dimensional zig-zag structure and three-dimensional double helical structure are found as a result of the transition controlled by the prolateness parameter. Formation of double helical structures is found to be a stable structure resulted from the transition associated with the instability of angular perturbations on double strings. Analytical perturbation study supports the findings of numerical simulations.
(Paper #2)

Theory

In a cryogenic plasma Debye length becomes smaller and the shielding length becomes comparable with a dust size. Dust charging in a cryogenic plasma is examined in detail by considering the polarization effect on a dust particle due to charged plasma particles. Electrons are found to be attracted when they come closer to a dust particle within a distance from the surface of a dust particle given by $\Delta r = a\left((\varepsilon-1)\exp\left(a/\lambda_{\mathrm{D}}\right)/2\left|Z_{\mathrm{d}}\right|(1+a/\lambda_{\mathrm{D}})\left(2\varepsilon+3\right)\right)^{1/2}$, where a is a radius of a spherical dust particle, ε is a dielectric constant of the dust particle, Z_{d} is the charge state of a dust particle, and λ_{D} is the Debye length, while ions are trapped at a certain distance around a dust particle without hitting the surface. Negatively charged dust particles form two dimensional crystal structures and the displacement from the equilibrium positions shows normal modes with a dispersion relation. Experimental study shows the unique dependence of dust charges on a cryogenic temperature. (Paper #3)

The quantum modulational and filamentational instabilities of monochromatic Langmuir pump wave is investigated, using 'renormalized' quantum linear and nonlinear plasma polarization responses. Furthermore, we also demonstrated how quantum corrections affect the instabilities or the instabilities growth rate. (Paper #4)

The properties of the low frequency surface waves in an inhomogeneous, magnetized collisional dusty plasma are investigated in the present work. The inhomogeneity is modelled by the two distinct regions of the dusty medium with different dust densities. The external magnetic field is assumed to be oriented along the interface dividing the two medium. It is shown that the collision between the plasma particles, which is responsible for the relative drift, affects the propagation of the surface waves via Hall diffusion of the field. The propagation properties depend on the number of charge carried by the dust grains which in turn depends on the ambient plasma temperature and the grain size. (Paper #6)

List of Publications:

a) Papers published in peer-reviewed journals (See attached published papers in pdf)

1. Y. Saitou, Y. Nakamura, T. Kamimura, and O. Ishihara, Bow shock formation in a complex plasma, Physical Review Letters **108**, 065004 (1-4) (2012).
2. Tetsuo Kamimura and Osamu Ishihara, Coulomb Double Helical Structure, Physical Review E **85**, 016406(1-7) (2012).
3. O. Ishihara, Low-dimensional structures in a complex cryogenic plasma, Plasma Physics and Controlled Fusion **54**, 124020-1~7(2012).
4. F. Sayed, S. V. Vladimirov, Yu. Tyshetskiy, and O. Ishihara, Modulational interactions in quantum plasmas, Physics of Plasma **20**, 072116-1~11 (2013).
5. Y. Saitou and O. Ishihara, Dynamic Circulation in Complex Plasma, Physical Review Letters **111**, 185003-1~5 (2013).
6. B. P. Pandey, S. V. Vladimirov and O. Ishihara, Surface waves in the magnetized, collisional dusty plasmas, Physics of Plasmas **20**, 103703-1~5 (2013).
7. Y. Saitou, A. A. Samarian, and O. Ishihara, Differential dust disk rotation in a complex plasma with magnetic field, Proceedings of the 12th Asia Pacific Physics Conference, JPS (Physical Society of Japan) Conference Proceedings **1**, 015012-1~4 (2014).
8. M. Shindo, A. Samarian, and O. Ishihara, Dynamics of Charged Dust near Liquid Helium Surface, Proceedings of the 12th Asia Pacific Physics Conference, JPS (Physical Sociey of Japan) Conference Proceedings **1**, 015049-1~4(2014). 10.7566/JPSCP.1.015049
9. Y. Saitou and O. Ishihara, Tempest in a Glass Tube - A Helical Vortex Formation in a Complex Plasma, Journal of Plasma Physics, pp. 1-8, Special Issue Physics of Dusty Plasmas (August 2014).

b) Conference Proceedings

1. O. Ishihara, Low-dimensional structures in a complex cryogenic plasma, The Joint EPS/ICPP (39 th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics), Stockholm, July 2-6, 2012) Invited talk. I1.304.
2. M. Chikasue, A.Samarian and O. Ishihara, Dust acoustic waves in a diffused plasma under subzero temperatures, The Joint EPS/ICPP (39 th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics), Stockholm, July 2-6, 2012). P4.131.
3. A. Samarian, Y. Saitou, A. J. Choudhury and O. Ishihara, Dust dynamics in a strong axial magnetic field:Galaxy-like rotation, The Joint EPS/ICPP (39 th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics), Stockholm, July 2-6, 2012). P4.129.
4. Y. Nakamura、Y. Saitou and O. Ishihara, Electric charges of microparticles in a complex plasma with an external magnetic field, The Joint EPS/ICPP (39 th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics), Stockholm, July 2-6, 2012). P4.137.
5. Y. Saitou, Y. Nakamura, T. Kamimura and O. Ishihara, Dust Particle Trapping in a Void Boundary in the Presence of Dust Flow, The Joint EPS/ICPP (39 th European Physical Society Conference on Plasma Physics /The 16th International Congress on Plasma Physics), Stockholm, July 2-6, 2012). P1.128.
6. Y. Saitou, A. A. Samarian, and O. Ishihara, Differential dust disk rotation in a complex plasma with magnetic field, APPC12, The 12th Asia Pacific Physics Conference, July 14-19, 2013, International Conference Hall, Makuhari Messe, Chiba Japan. D1-4-O4
7. M. Shindo, A. Samarian , O. Ishihara, Dust particles trapped under the liquid helium surface,

APPC12 ,The 12th Asia Pacific Physics Conference, July 14-19, 2013, International Conference Hall, Makuhari Messe, Chiba Japan. D1-PTh-15

8. F. Sayed, S. V. Vladimirov, Yu. Tyshetskiy, and O. Ishihara, Modulational and filamentational instabilities of monochromatic Langmuir pump wave in quantum plasmas, APPC12 ,The 12th Asia Pacific Physics Conference, July 14-19, 2013, International Conference Hall, Makuhari Messe, Chiba Japan. D1-PTh-19
9. F. Sayed, S. V. Vladimirov, Yu. Tyshetskiy, and O. Ishihara, Soliton solution of the Zakharov equations in quantum plasmas, APPC12 ,The 12th Asia Pacific Physics Conference, July 14-19, 2013, International Conference Hall, Makuhari Messe, Chiba Japan. D1-PTh-18
10. O. Ishihara, Dynamics of Charged Dust Particles in a Complex Plasma, The 8th Asia-Pacific International Symposium on the Basics and Applications of Plasma Technology (APSPT-8) National Chiao Tung University (NCTU), Hsinchu, Taiwan (December 20-22, 2013). Invited talk.

c) Domestic conferences

1. Y. Saitou, A. Samarian and O. Ishihara, Frozen dust waves: Evolution of dust sound speed in decaying complex plasma, 13th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 7-8, 2012).
2. Y. Saitou, A. Samarian and O. Ishihara, Vortex Formation in a Complex Plasma, 14th Workshop on fine particle plasmas (National Institute of Fusion Science, Toki, Japan, Dec. 12-13, 2013).
3. M. Shindo, T. Wakiya, S. Pineda, A. Samarian and O. Ishihara, Charged Complex under the Liquid Helium Surface, (National Institute of Fusion Science, Toki, Japan, Dec. 12-13, 2013).

d) patents that resulted from this work.

N/A